Medical Engineering and Physics 000 (2016) 1–9

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

In-vitro investigation of the hemodynamic responses of the cerebral, coronary and renal circulations with a rotary blood pump installed in the descending aorta

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ARTICLE INFO

Article history:
Received 8 July 2016
Revised 2 November 2016
Accepted 13 November 2016
Available online xxx

Keywords:
Cardiovascular simulator
Blood pump
MCS
RBP
VAD

ABSTRACT

This study investigates the hemodynamic responses of the cardiovascular system when a rotary blood pump is operating in the descending aorta, with a focus on the cerebral, coronary and renal autoregulation, using our in-house cardiovascular emulator. Several improvements have been made from our previous studies. A novel coronary system was developed to replicate the native coronary perfusion. Three pinch valves actuated by stepper motors were used to simulate the regional autoregulation systems of the native cerebral, coronary and renal circulations. A rotary pump was installed in the descending aorta, in series with the heart, and the hemodynamic responses of the cardiovascular system were investigated with a focus on cerebral, coronary and renal circulation over a wide range of pump rotor speeds. Experiments were performed twice, once with the autoregulation systems active and once with the autoregulation systems inactive, to reflect that there will be some impairment of autoregulatory systems in a patient with heart failure. It was shown that by increasing the rotor speed to 3000 rpm, the cardiac output was improved from 2.9 to 4.1 L/min as a result of an afterload reduction induced by the pressure drop upstream of the pump. The magnitudes of changes in perfusion in the cerebral, coronary and renal circulations were recorded with regional autoregulation systems active and inactive.

1. Introduction

The number of deaths caused by Heart Failure (HF) has decreased during the past decade in developed countries, yet HF is still the leading cause of deaths in the world. In the United States, in a 10 year period from 2001 to 2011, death rates attributable to HF and the actual number of HF deaths declined by 30.8% and 15.5% per year respectively, yet in 2011 HF still accounted for 31.3% of all deaths [1]. Despite all available therapies to this problem, heart transplant is the main option for end-stage HF patients. However, with a limited number of heart donors available annually (2500 for USA, 1400 Europe and 300 other countries [2,3]) the rate of mortality remains very high for patients on and off the waiting list.

As a result, Rotary Blood Pumps (RBP) have become vital for end-stage HF patients as a bridge to transplantation or destination therapy [4,5]. One of the challenges with the traditional RBPs is their highly invasive implantation procedure which makes many elderly and ill patients ineligible for the surgery. This has encouraged many researchers to investigate new approaches with potential for minimally invasive surgery [6,7].

Transaortic or in-series miniature RBPs, distant from the heart, are one minimally invasive solution [8–11]. The implantation of a RBP in the Descending Aorta (DA), in series with the heart, has been of growing interest among various groups [6,8,12–15]. It was reported that the insertion of an RBP device in the descending aorta leads to an improved cardiac output, yet there is a question related to the impact of the pressure drop generated upstream of the pump on blood perfusion in the upper extremities, particularly the brain and heart [6,12,13,16]. In addition, there is a concern associated with the effect of the pressure rise downstream of the pump on lower extremities, particularly the kidneys [17].

The regional autoregulation systems, which maintain a constant flow rate to vital organs during changing local perfusion pressure,

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http://dx.doi.org/10.1016/j.medengphy.2016.11.006
1350-4533/

Nomenclature

Subscripts

ao	aortic
dia	diastolic
mean	mean
pp	pulse pressure
sys	systolic

Abbreviations and acronyms

AoP	aortic pressure
AV	aortic valve
C	compliance
CHF	congestive heart failure
CeF	cerebral flow rate
CeP	cerebral pressure
CO	cardiac output
CoF	coronary flow rate
CoP	coronary pressure
CVR	cerebrovascular resistance
DA	descending aorta
F	flow-meter
LA	left atrium
LV	left ventricle
LM	linear motor
LVP	left ventricular pressure
MCS	mechanical circulatory support
MV	mitral valve
P	pressure
PV	pulmonic valve
Q	flow rate
RBP	rotary blood pump
RA	right atrium
ReP	renal pressure
ReF	renal flow rate
RV	right ventricle
RVP	right ventricle pressure
SCVL	simulator of cardiovascular loops
SyF	systemic flow
TV	tricuspid valve

are present in many organs of the native cardiovascular system, however these are most pronounced in the heart, brain and kidneys [18]. The cerebral autoregulation is a vital homeostatic mechanism to maintain the blood supply to the brain in the event of changing perfusion pressure. For a healthy person, the cerebral circulation is autoregulated within wide limits of mean aortic pressure from 60 to 120 mmHg [19,20]. The coronary circulation maintains the blood supply to the heart and is autoregulated within 45–130 mmHg in a healthy person [21]. The renal autoregulation has been extensively investigated in prior studies [22,23]. In a native human body the renal blood supply is relatively constant when the mean arterial pressure varies between 90 and 180 mmHg [22]. It must be noted that various pathological conditions, including hypertension, hypotension and a change in arterial CO_2 level can alter the upper and lower limits of the autoregulated region [24].

The aim of this study is to investigate the hemodynamic responses of the cardiovascular system when a rotary pump is operating in the descending aorta with a focus on the cerebral, coronary and renal circulation. Since the regional autoregulation can be impaired in heart failure patients, the hemodynamic response is investigated with intact and impaired regional autoregulation. An expected outcome is to estimate what level of support is feasible while avoiding the previously mentioned risk of drops in perfusion to the coronary and cerebral circulations.

The objectives of this study are met using our in-house multi-chamber Simulator of Cardio-Vascular Loops (SCVL). Cardiovascular simulators offer a more controlled and inexpensive platform to evaluate the performance of existing blood-contacting devices as well as new medical concepts, prior to in-vivo studies. In recent years, much progress has been made in the design and development of cardiovascular simulators with close similarity to a native system for research and training [25–28].

In the present study, several improvements have been made from our previous studies [6,12,13,29]. The coronary perfusion mechanism which causes the heart to be perfused only during diastole was implemented using a solenoid valve. In addition, the coronary and renal autoregulation circulations, similar to the cerebral autoregulation mechanism presented in our previous study [29], were integrated into the SCVL system, with autoregulation limits determined from the clinical data.

2. Methodology

The native cardiovascular system of an adult human was emulated using our in-house SCVL system, as shown in the schematic diagram of Fig. 1.

Four elastic rubber chambers were used to model the native heart chambers. The left and right ventricles (LV and RV) had a volume of 100 mL and the left and right atrium (LA and RA) had a volume of 50 mL. Four linear motors (P01-37× 120 from LinMot, Spreitenbach, Switzerland) were employed to simulate the contraction and dilation of the ventricle and atrium chambers. Two trajectory time-varying functions extracted from the real time left ventricle and left atrium volume, as described in our previous study [29], were employed to actuate the four linear motors. Fig. 2 shows the simultaneous graphs of trajectory time-varying functions of the ventricles and atria for an intact heart. Each function can be scaled up or down in order to replicate various physiological and pathological conditions.

Four prosthetic heart valves (Medtronic, Minneapolis, Minnesota, USA) modelling the aortic, mitral, pulmonary and tricuspid valves were used to ensure unidirectional flow in the vicinity of each chamber. The systemic and pulmonary circulations are replicated using 24 mm diameter rubber tubing, while smaller arteries are replicated using 12 mm diameter rubber tubing. A blood analog solution comprising of 65 wt% water and 35 wt% glycerol was used as the working fluid, as in the study conducted by Pantalos et al. [27].

Five pressure transducers (PMP 5074, precision ± 0.1 FS BSL) from General Electric, Billerica, MA, USA were used to simultaneously measure the Left Ventricle Pressure (LVP), Aortic Pressure (AoP), Right Ventricle Pressure (RVP), Cerebral Pressure (CeP) and Renal Pressure (ReP). The Coronary Pressure (CoP) was defined as equal to the AoP.

A number of Hoffman clips were used to manually control the systemic and pulmonary resistance level to allow tuning of the SCVL system. Three electromagnetic flow-meters (SITRANS F M MAG 1100 F, precision 0.4% ± of reading, from Siemens, Munich, Germany) were employed to measure the Cerebral Flow (CeF), Coronary Flow (CoF) and Renal Flow (ReF), respectively and an ultrasonic flow-meter (Cynergy UF Flow, C3, precision 3% of reading) (Cynergy UF Flow, C3) was used to measure the Systemic Flow (SyF). The sum of these flows gives the Cardiac Output (CO). The vascular distensibility of the systemic and pulmonary circulations was replicated using a number of compliance units developed in our previous experiment [29]. The compliance level for each unit can be adjusted to match the vascular distensibility of a native system for various pathological conditions.

A parallel configuration of a solenoid valve and narrow tubing was used to model the coronary perfusion mechanism, as shown

Please cite this article as: M.A. Rezaienia et al., In-vitro investigation of the hemodynamic responses of the cerebral, coronary and renal circulations with a rotary blood pump installed in the descending aorta, Medical Engineering and Physics (2016), http://dx.doi.org/10.1016/j.medengphy.2016.11.006